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MODERN FEM TOOLS – AN EXAMPLE OF CABLES INSTALLED IN DUCT-BANKS

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ABSTRACT

In many places around the world cables are installed in duct-banks. The duct-bank has in all practical cases normally a lower thermal resistivity than the surrounding soil.
With modern FEM-tools it has in this paper been shown that the external thermal resistance and the effect of backfilling in some cases can increase the rating of the system compared to analytical tools according to standards. That is, the IEC and Neher McGrath formulas are not in perfect agreement with the results obtained from FEM.
In very extreme cases, for example a rectangular duct-bank with dimensions 1x0,33 m and large difference in thermal resistivities between soil and duct-bank, the rating may be increased by up to 30% compared to IEC and N-M if incorporating both rectangular shape of duct-bank and backfill. For more common conditions, one may however ask if backfill is necessary at all.

KEYWORDS

FEM, cable ampacity, duct-bank, backfill, soil drying out

INTRODUCTION

The aim of this paper is to address some contributions of modern FEM-tools, which may give a better understanding of thermal phenomena attributed to cables installed in duct-banks.
The modeling of the duct itself is not described here. Rather the agreement with IEC 60287 and Neher McGrath formulae for the external thermal resistance of the duct-bank is discussed. In IEC and N-M an equivalent diameter is introduced to make a transformation from rectangular to circular shape of the duct-bank possible. It will be shown that this transformation is not perfect.
Furthermore, the effect of thermal backfill is introduced and some corrective factors are given in the form of a diagram in order to give some rule of thumbs.
It is in this paper, however, not the aim to give any contribution to IEC or N-M, i.e. to suggest any modification therein. It is instead meant to show the possibilities of using modern FEM-tools and to make checks and comparisons possible with analytical solutions.
Maybe, modern FEM-tools, which give very exact solutions and which become more sophisticated, will be introduced as a standard calculation tool in the future. For example, IEC and N-M does not take into account the air inside adjacent ducts into account, i.e. the complete duct-bank is in fact not filled with concrete. Such a configuration, taking adjacent air-filled ducts into account, can easily be modeled in a modern FEM-tool.

CALCULATION OF T_4 IN IEC AND N-M

According to IEC 60287 [1] and Neher-McGrath [2] analytical models, the external thermal resistance of a buried cable, duct or duct-bank must satisfy the following two important conditions:

- The ground surface is treated as an isothermal surface, thus enabling the cable to be mirrored in this plane
- The thermal resistivity is constant versus space and time

Following these pre-conditions, any isotherm (harmonic circle) in the soil is calculated according to equation 1:

$$T_4 = \frac{\rho_e}{2\pi} ln\left(u + \sqrt{u^2 - 1}\right) = \frac{\rho_e}{2\pi} G \qquad [1]$$

ρ_e is the thermal resistivity of soil
$u = L/r_b$
L is the distance from the surface of the ground to the cable axis
r_b is the external radius of the isotherm

The isothermal circles from a single isolated buried cable are shown in Figure 1. It can be noticed that the bigger the isotherm is, the bigger is the offset between the center of the circle and the heat source generating the isotherm. This offset is taken into account and is included in the ln-expression, G, in equation 1.

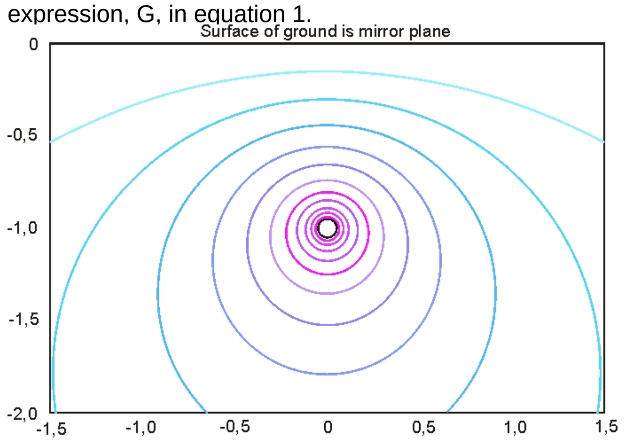

Figure 1. Isothermal harmonic circles for a single isolated buried cable.

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Calculation of the offset

Consider an arbitrary circular isotherm of radius r_b, with centre at the depth L. The isotherm is generated by a heat line source +W and its mirror image –W in the surface plane. The line source is positioned with an offset ΔL from the centre of the circulate isotherm. Calculation of the offset ΔL is according figure 2.

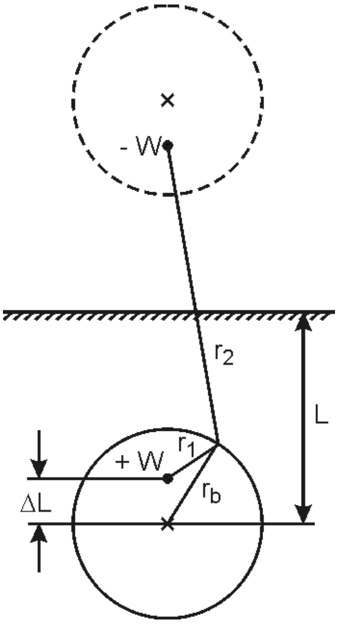

Figure 2. Mirroring of an isotherm in soil.

The circle in figure 2 is an isotherm if the temperature θ_{iso} in equation 2 is constant:

$$\theta_{iso} = W \frac{\rho_e}{2\pi} \ln\left(\frac{r_2}{r_1}\right) \qquad [2]$$

Since any isotherm has a constant temperature, the ratio of r_2 and r_1 must be constant. Thus;

$$\frac{r_2}{r_1} = \frac{2L-(r_b+\Delta L)}{r_b-\Delta L} = \frac{2L+(r_b-\Delta L)}{r_b+\Delta L} \qquad [3]$$

It follows;

$$\Delta L = r_b\left(u-\sqrt{u^2-1}\right) \qquad [4]$$

In equation 4 it is shown that the offset ΔL is approximately proportional to the size of the circular isotherm.

Calculation of T4 in duct-banks

When calculating the external thermal resistance T_4 for duct-banks, the rectangular shape of the duct-bank must be transformed to a circular isotherm (with equivalent diameter D_b) by using a formula similar to the one used in equation 1. However, since the duct-bank normally has a lower thermal resistivity, ρ_c, than the surrounding soil, the calculation of the total external thermal resistance is made in two steps:

- Firstly, the external thermal resistance of the hottest cable in the duct-bank is calculated, using the thermal resistivity ρ_c for the whole soil.
- Secondly, the difference in external thermal resistance resistivity between soil and duct-bank is calculated by using the equivalent diameter D_b of the duct-bank as a transition between duct-bank and soil.

In other words, the external thermal resistance is calculated according to equation 5 below:

$$T_{4-tot} = T_4(\rho_c) + \Delta T_4(\rho_e, \rho_c) \qquad [5]$$

$$\Delta T_4 = N\frac{(\rho_e-\rho_c)}{2\pi} ln\left(u+\sqrt{u^2-1}\right) \qquad [6]$$

N	number of cables in duct-bank
u	$=L/r_b$
L	center to duct-bank or circular isotherm

The transformation of the rectangular duct-bank with long side *y* and short side *x*, is not perfect and should be used only if the *y/x*-ratio is less than 3. In IEC and N-M, the calculation of D_b is given but can be rewritten to:

$$D_b = x\left(1+\left(\frac{y}{x}\right)^2\right)^{\frac{x}{2y}\left(\frac{4}{\pi}-\frac{x}{y}\right)} = x\cdot f\left(\frac{y}{x}\right) \qquad [7]$$

In equation 7 it is evident that the equivalent diameter of the duct-bank is proportional the shortest side of the duct-bank (*x*) and a function *f*, dependant on the ratio of the longest and shortest sides. The function *f* is shown in figure 3 below. It can be noticed that the function tends to decrease for ratios larger than 3.

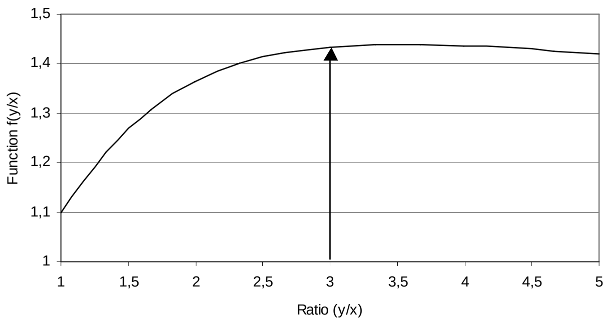

Figure 3. Factor to be multiplied with x (shortest side of duct-bank). Ratios of y/x larger than 3 is not included in IEC and N-M.

CORRECTION FACTORS - FEM VS. IEC, N-M

Under this paragraph we will investigate how well the transformation formulae used in IEC and N-M agree with modern calculation methods like FEM. We will further investigate how backfill of the same thermal resistivity as the duct-bank, will affect the external thermal resistance outside the duct-bank.

Correction factor, α between duct-bank and D_b

We want to find a correction factor, α, which can be used to proportionally multiply equation 6 with and thus get a better transformation formula.

Any closed surface, S, around N cables installed in a duct-bank, will have a total outward heat flux from S which equals the power loss of N cables. That is, the surface of a duct-bank will have the same outward heat flux as the isotherm, representing the duct-bank. A very important condition, though, is that the same amount of power loss from the cables is enclosed by both surfaces. As described earlier, the N cables in the duct-bank must then be positioned in the same point at distance ΔL from the center within the circular isotherm. If not, a circular isotherm cannot be achieved. It should be noted that the rectangular duct-bank surface itself, is not an isotherm.

The foregoing discussion can be expressed in mathematical form as follows:

$$W = w \cdot N = \frac{(\theta - \theta_a)}{\Delta T_4} = \frac{(\theta' - \theta_a)}{\Delta T_4'} \qquad [8]$$

where

θ	temperature of circular isotherm according to IEC and N-M
θ'	the average temperature value of the duct-bank boundary which is achieved from FEM
θ_a	the ambient temperature
w	power loss per cable in W/m

Now, θ' must be the corrective temperature of a new isotherm around the duct-bank. Thus, from equation 8:

$$\Delta T_4' = \Delta T_4 \left(\frac{\Delta\theta'}{\Delta\theta} \right) = \Delta T_4 \cdot \alpha \qquad [9]$$

Thus, an equivalent external thermal resistance outside the duct-bank can be found by using equation 9. Since $\alpha \leq 1$, the new circular isotherm and corresponding external thermal resistance $\Delta T'_4$, must have an equivalent diameter slightly larger than D_b, but this has not to be taken care of in equation 9.

To further explain the foregoing deduction, figure 4 has been included which represents a duct-bank (1000x667 mm) including 6 cables, each of heat loss w.

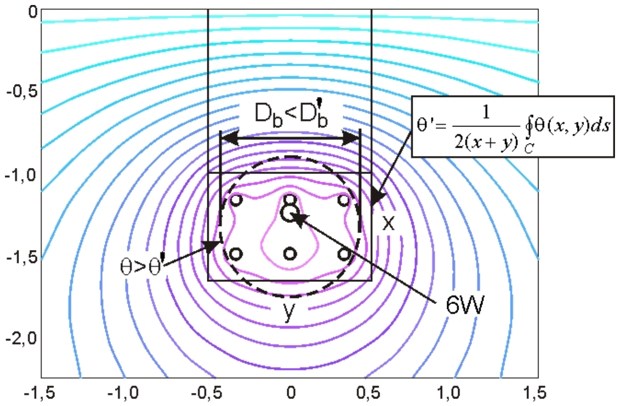

Figure 4. The idea behind the transformation from rectangular to circular shape of duct-bank, using FEM.

Correction factor, β for thermal backfilling

Another important issue for cable systems installed in duct-banks may be whether thermal backfilling is needed or not. It is then necessary to calculate this effect. We can therefore use the same procedure as before and create another correction factor, β, in order to take into account the effect of thermal backfill.
As before, we have then:

$$\Delta T_4'' = \frac{\Delta\theta''}{\Delta\theta'} \Delta T_4' = \beta \cdot \Delta T_4' \qquad [10]$$

In the FEM-program we then integrate around the duct-bank contour once more but with thermal backfill above duct-bank. The thermal backfill has the same thermal resistivity as the duct-bank, in this paper.
If the combined effect of the correction for duct-bank transformation (α) and thermal backfill (β) is taken into account, the new external thermal resistance outside the duct-bank is:

$$\Delta T_4^o = \alpha \cdot \beta \cdot \Delta T_4 \qquad [11]$$

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RESULTS FROM FEM-CALCULATIONS

Conditions for FEM-calculation

The FEM-program has been used to extract both correction factors described above. The following conditions have been used:

- y/x-ratios range from 1 to 3
- the ratio of thermal resistivity in soil and thermal resistivity in duct-bank ranges from 1 to 5
- in case of backfill material above duct-bank, the thermal resistivity always equals the duct-bank's thermal resistivity
- the depth to top of duct-bank has been calculated for 1 and 3 m, respectively
- the distance between cables are 1/3 m
- the duct-bank dimensions are 1x1, 1x0,67 and 1x0,33 m, respectively.

The following duct-bank configurations have been used in calculations :

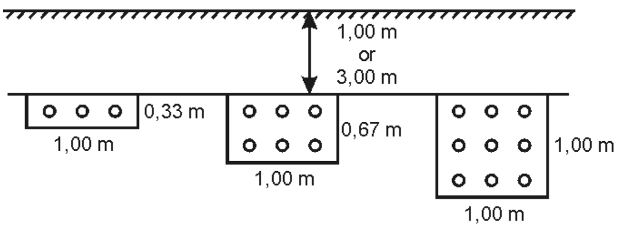

Figure 5. Duct-bank layouts for FEM-calculation.

Results

In Table 1 and 2, the results for 1 and 3 m depth to top of duct-bank are given for calculation of α.

Table 1. α– and β-factor for 1 m depth to top of duct-bank.

Layout	α	β
ρ_s/ρ_c=1.0		
1x1 m	1,00	N.A
1x0,67 m	0,89	N.A.
1x0,33 m	0,74	N.A.
ρ_s/ρ_c=1.5		
1x1 m	0,99	0,90
1x0,67 m	0,88	0,89
1x0,33 m	0,74	0,87
ρ_s/ρ_c=2.0		
1x1 m	0,98	0,83
1x0,67 m	0,88	0,81
1x0,33 m	0,73	0,78
ρ_s/ρ_c=3.0		
1x1 m	0,98	0,71
1x0,67 m	0,87	0,68
1x0,33 m	0,73	0,64
ρ_s/ρ_c=5.0		
1x1 m	0,97	0,56
1x0,67 m	0,86	0,52
1x0,33 m	0,72	0,48

Table 2. α– and β-factor for 3 m depth to top of duct-bank.

Layout	α	β
ρ_s/ρ_c=1.0		
1x1 m	0,99	N.A
1x0,67 m	0,91	N.A.
1x0,33 m	0,81	N.A.
ρ_s/ρ_c=1.5		
1x1 m	0,98	0,94
1x0,67 m	0,91	0,93
1x0,33 m	0,81	0,92
ρ_s/ρ_c=2.0		
1x1 m	0,98	0,88
1x0,67 m	0,91	0,87
1x0,33 m	0,80	0,85
ρ_s/ρ_c=3.0		
1x1 m	0,98	0,79
1x0,67 m	0,91	0,78
1x0,33 m	0,80	0,75
ρ_s/ρ_c=5.0		
1x1 m	0,98	0,67
1x0,67 m	0,91	0,64
1x0,33 m	0,80	0,61

Some interesting conclusions can be made from Tables 1 and 2 :

- There is good agreement (α close to 1) between the IEC, N-M equivalent isotherm (D_b) and FEM for quadratic shaped duct-banks
- The agreement between rectangular duct-banks and IEC, N-M is less accurate ($\alpha \approx$ 0,7) for y/x-ratios less than 3 and depths less than 3 m.
- The influence of backfilling is almost independent on the shape of the duct-bank.
- The influence of backfilling varies a lot with the ratio of soil and backfill thermal resistivities
- The influence of backfilling is slightly higher at shallow depths rather than deeper.

Now, selecting the maximum values of α for 1 and 3 meter will give us the most conservative values for different shapes of duct-banks. The worst case is when the thermal resistivity is the same in duct-bank and soil. See figure 6.

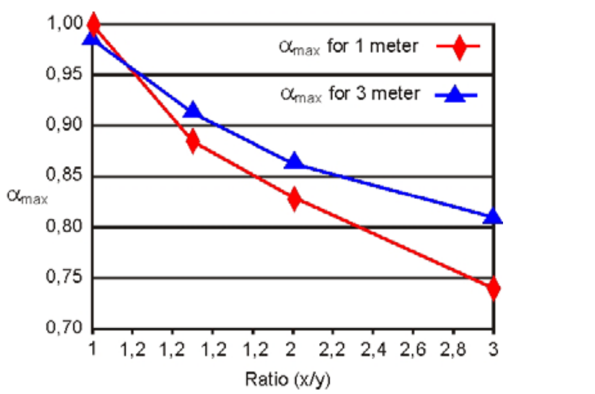

Figure 6. Conservative corrective factor, α_{max} for duct-bank transformation.

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The effect of backfilling can be simulated in the same way. In figure 7 the most conservative values from Table 1 and 2 are shown.

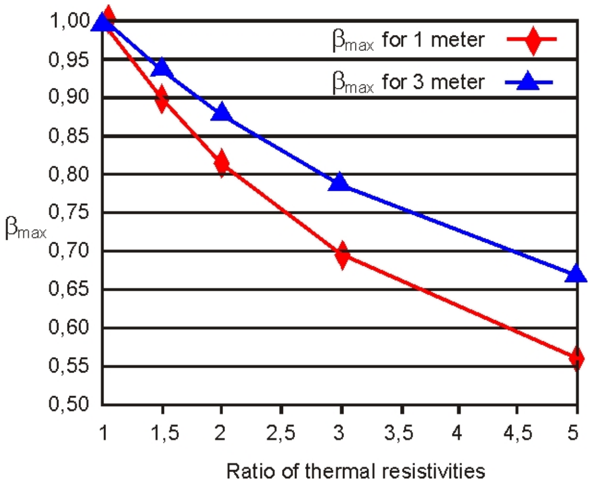

Figure 7. Conservative corrective factor, β_{max}, due to backfilling.

Sensitivity to height/width and position of cables

If, however, the duct-bank has a smaller width than height, i.e. the duct-bank dimensions are 0,67x1 or 0,33x1 m, the correction factor α will be almost the same, only some percent larger.

In the same way, the position of the cables in the duct-bank plays any big role at all. If for example, all the cables in the duct-bank with dimensions 1x0,67 m are all placed in the centre of the duct-bank, the correction factor α and β are the same.

PRACTICAL EXAMPLE

To further exemplify the achievable increase in ampacity for duct-bank installations, a calculation with the following conditions has been made:

- 132 kV XLPE cable, 1200 mm^2 Cu-segment
- 3 cables installed in a duct-bank with dimensions 1x0,33 m
- Thermal resistivity in duct-bank is 0,6 Km/W
- The ratios between soil and duct-bank thermal resistivities are 1.5, 2, 3 and 5.
- The base current ampacity is 100% and is calculated according to IEC, N-M, strictly.
- The "worst-case" factors are used.

The results are recorded in Table 3. The reason for choosing a duct-bank size of 1x0,33 m is just to exemplify a dimension, which gives the largest difference compared to IEC and N-M calculation methods.

Table 3. Revised rating for cables in duct-bank and with backfilling above duct-bank. Example from 1x0,33 m sized duct-bank.

Layout	I_α (%)	$I_{\alpha\ \beta}$ (%)
ρ_s/ρ_c=1.5		
1 m depth	102	103
3 m depth	102	103
ρ_s/ρ_c=2.0		
1 m depth	104	107
3 m depth	104	106
ρ_s/ρ_c=3.0		
1 m depth	107	115
3 m depth	105	112
ρ_s/ρ_c=5.0		
1 m depth	110	130
3 m depth	108	124

Some conclusions can be made from Table 3 :

- For installation depths less than 3 m to top of duct-bank and no backfill, the increase in rating is less than 10 %, independently of the soil thermal resistivity outside the duct-bank.
- Backfilling has a big effect on the rating for big differences in soil and duct-bank thermal resistivities.
- For a thermal resistivity ratio less than 3, it should be considered if it is necessary with backfill or not.

It should further be noticed that, in a normal situation, a 3-m deep installation may constitute the worst-case scenario along the cable route even if the ambient temperature may be less than at 1 m, for example. This means that the deep installation rating may be decreased in relation to the 1-m installation rating and the effect of backfilling may not be so good as indicated in Table 3 in a real situation. Increased spacing between cables may be another possible solution to come around this issue at deep installations, however.

ECONOMICAL CONSIDERATIONS

Is backfill necessary or not? Is backfill economically justified?
These questions can be answered only for the specific project. It may be interesting, however, to calculate the copper weight needed, to compensate for the increased rating due to the backfill (β) and the developed duct-bank transformation (α).

For small changes in rating a revised copper cross-section area may be expressed according to equation 12:

$$A^o_{Cu} \approx A_{Cu} \cdot \left(\frac{I^o}{I} \right)^2 \qquad [12]$$

For example, at 3 m depth and a thermal resistivity ratio of 3, only the backfilling will increase the rating with 1.12/1.07=1.04, i.e. with 4 %. This will in turn, give an approximate increased cross-section of copper of 8.5%, i.e. about 1300 mm^2.
Since the rating versus the copper cross-section area is not linear and especially for large cross-sections the increase in rating is marginal due to the skin effect, it is likely that backfill may be more economically favourable for cross-section areas larger than 1200 mm^2.

The specific situation must decide whether 100 mm^2 of copper is economically justified to add instead of using thermal backfill.

DRYING OUT CLOSE TO DUCT-BANK

Losses from congestion of cables in a duct-bank can give rise to high temperatures close to the duct-bank and dry out the backfill. In the analysing methods used above, drying out of the backfill was not considered close to the duct-bank. Methods according to IEC 60287 are possible to apply if the number of different ambient materials is limited but the methods are complicated and it is difficult to realize the correctness of such calculations. In this case is FEM a powerful tool.
Figure 8 shows a typical duct-bank used in USA. The figure is a cut of the FEM model that includes ambient ground to the surface of the ground.

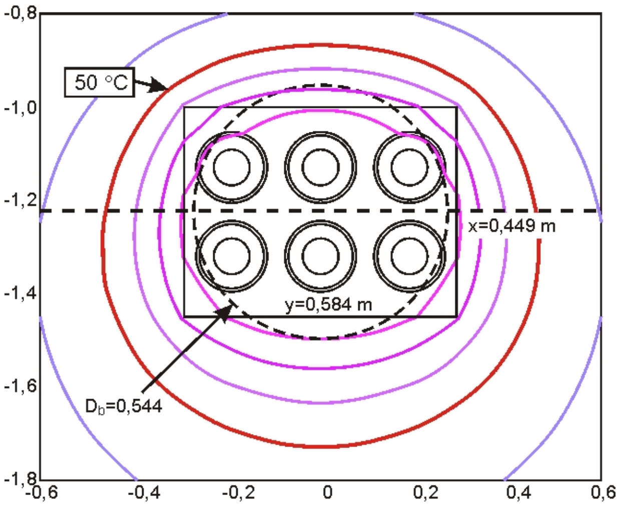

Figure 8. Installation of 138 kV cables in concrete duct-bank.

The concrete duct-bank is buried 1 m to top of the bank and the polymeric ducts are air-filled.
The model is made up of four types of domains, the ambient ground, the duct-bank, the polymeric ducts and the air space between cable surface and inside of ducts. Each domain has its own thermal data. Only the surfaces of the cables are drawn mid in the ducts. The reason is that the thermal resistance of the air space described according IEC 60287, presumes radial heat flux between cable and duct surface. The cable itself is not included in the FEM model as its thermal model is easy described according IEC 60287.

The thermal resistivity of wet ground is ρ_{wet} = 1,2 K×m/W and dried out ground ρ_{dry} = 2,5 K×m/W. The thermal resistivity of the concrete duct is ρ_{con} = 1,0 K×m/W. Figure 8 shows isotherms close to the duct when cable losses are 15 W/m. Drying out is assumed inside the 50 °C isotherm. The thermal resistance (T_4) of the duct-bank is 0,410 K×m/W when no draying out is considered. This gives a temperature of 57 °C of the duct-bank surface when the ambient temperature is 20 °C.
It is possible to couple the thermal resistivities in the domains into one common variable. This variable is plotted in figure 9 along the dashed line shown in figure 8.

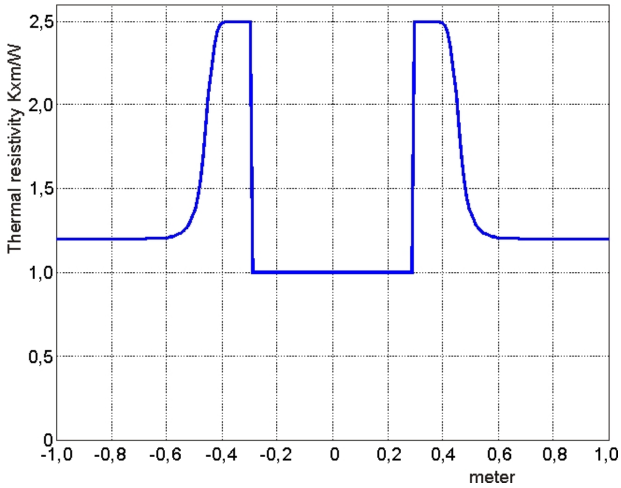

Figure 9. Thermal resistivity plotted along the dashed line in figure 8.

Figure 9 shows how the thermal resistivity of ground changes from wet to dry state close to the duct-bank. The thermal resistivity of ground is in this case a composition of two resistivities described with distribution curves with temperature as dependent variable. In this way a real drying out phenomenon is described. Advanced FEM programs can handle the simplified description of stepwise change between dry and wet state without instability problems.

CONCLUSION

It has been shown that modern FEM-tools can be used effectively to check the correctness of IEC and N-M in different situations. Drawing editors and possibility to import different drawing formats have developed in such a way that complicated structures are easily handled today. Post-processing and graphical presentation of data involves efficient interpretation of calculations. There are a lot more practical cases where FEM may be used to check calculations. For example when steel pipes are used in directional drilling, the magnetic effect of the pipe will affect the rating of the circuit. This will be shown in a later paper.

REFERENCES

[1] IEC 60287 Electrical cables, Calculation of the current rating, Part 2-1: Thermal resistance

[2] J.H. Neher and M.H. McGrath. “The Calculation of Temperature Rise and Load capability of Cable Systems” *AIEE Transactions on Power Apparatus and Systems*, vol 76, October 1957.